REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-01-0188

1. REPORT DATE *(DD-MM-YYYY)*
17 Apr 2008

2. REPORT TYPE
REPRINT

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Evershed Flow, Oscillations, and Sunspot Structure

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
61102F

5d. PROJECT NUMBER
2301

5e. TASK NUMBER
RD

5f. WORK UNIT NUMBER
A1

6. AUTHORS
K.S. Balasubramaniam, A.A. Petsov*, and S. Olmschenk**

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory/RVBXS
Space Weather Center of Excellence
Sunspot, NM 88349

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RV-HA-TR-2008-1049

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RVBXS

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; distribution unlimited.

13. SUPPLEMENTARY NOTES *National Solar observatory, Sunspot, NM 88349 **FOCUS Center and Department of Physics, University of Michigan, Ann Arbor, Michigan 48109
REPRINTED FROM: Subsurface and Atmospheric Influences on Solar Activity, ASP Conference Series, Vol. 383, 2008

14. ABSTRACT
Using high resolution spectroscopy at high cadence, we probe oscillatory properties of the Evershed effect flows. We employ Doppler measurements in several spectral lines to show that the Evershed flow is modulated at periods lasting a few tens of minutes, at the photosphere and chromosphere. The phase of this modulation is always outward irrespective of whether the spectral line originates in the photosphere or chromospheres. From a power-spectrum analysis, we show that periods of peak power shift to longer periods as the magnetic field increases (going from the umbra to the outer penumbra), at photospheric levels. At the chromospheres the periods shift to longer periods as the magnetic field shifts from stronger to weaker fields. An analysis of these phenomena and their influence on the sunspot structure is presented.

15. SUBJECT TERMS
Sun Sunspots Solar oscillations Spectroscopy Evershed effect Solar activity

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCL	UNCL	UNCL	UNL		K.S. Balasubramaniam
					19B. TELEPHONE NUMBER *(Include area code)*

SUBSURFACE AND ATMOSPHERIC INFLUENCES ON SOLAR ACTIVITY
ASP Conference Series, Vol. 383, 2008
R. Howe, R. Komm, K. Balasubramaniam, and G. J. D. Petrie

Evershed Flow, Oscillations, and Sunspot Structure

K. S. Balasubramaniam,[1,2] A. A. Pevtsov,[2] and S. Olmschenk[2,3]

Abstract. Using high resolution spectroscopy at high cadence, we probe oscillatory properties of the Evershed effect flows. We employ Doppler measurements in several spectral lines to show that the Evershed flow is modulated at periods lasting a few tens of minutes, at the photosphere and chromosphere. The phase of this modulation is always outward propagating irrespective of whether the spectral line originates in the photosphere or chromosphere. From a power-spectrum analysis, we show that periods of peak power shift to longer periods as magnetic field strength increases (going from the umbra to the outer penumbra), at photospheric levels. At the chromosphere the periods shift to longer periods as the magnetic field shifts from stronger to weaker fields. An analysis of these phenomena and their influence on the sunspot structure will be presented.

1. Introduction

Solar oscillations are modulated by the magnetic field. Studies of oscillations in sunspots are particularly useful towards an understanding of magnetohydrodynamic wave-propagation in the solar plasma that is influenced by temperature/density stratification and the strength/orientation of the magnetic field. For a comprehensive review we refer the reader to Bogdan (2000).

Competing models for understanding the interaction of magnetic field and Evershed flow in sunspot penumbrae have had limited success in attributing physical mechanisms to explain the Doppler behavior. Significant among them are the siphon flow models, moving flux-tube models, and the uncombed penumbral model (see Solanki 2003 for a detailed review).

Some of these models suggest that Evershed flows may have an oscillatory pattern. For example, in the siphon flow model, a gas (and hence, magnetic) pressure difference at footpoints will send a "parcel" of material streaming from one footpoint to the other. However, pressure difference will diminish once the parcel reaches the opposite footpoint, and the flow will stop until magnetic forces restore the pressure difference again. Given a typical size of penumbral filaments and speed of Evershed flows one should expect flow modulations on the order of 10–15 minutes. Similar intermittency can be present in the moving flux-tube model, although the driving force is not the pressure but temperature difference. The modulation of sunspot oscillations in the presence of sunspot

[1] Air Force Research Labs, Space Weather Center of Excellence, Sunspot, NM 88349, USA, NM 88349, USA

[2] National Solar Observatory, Sunspot, NM 88349, USA

[3] FOCUS Center and Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA

magnetic fields and its influence on sunspot models will also help us further understand the propagation of magneto-acoustic waves (see, e.g., Staude et al. 1999; Bogdan et al. 2003; Rüedi & Cally 2003; Crouch & Cally 2005). Hence, integrating sunspot vector magnetic fields and sunspot oscillation measurements with structural models of sunspots is critical to understanding the influence of the solar magnetic field on activity. Several previous papers did report the presence of an oscillatory pattern in Evershed flows (e.g., Rimmele 1995; Rouppe van der Voort 2003 and references therein). However, a comprehensive study of this aspect of Evershed flows involving both photospheric and chromospheric heights in the solar atmosphere is largely nonexistent. In the spirit of such research, we present a preliminary understanding of measured sunspot oscillations that can serve as a basis for extended research into the propagation of sunspot waves and oscillations. We present the spatial and temporal behavior of oscillations, and its influence on the Evershed flow and the sunspot structure.

2. Spectroscopic Observations and Reduction

We acquired high resolution spectroscopic measurements across a selected sunspot (NOAA 0198, 22 November, 2003; 18S 04W; 15:58 – 17:54 UT). The data were taken at the Dunn Solar Telescope (DST) at the National Solar Observatory (NSO) at Sacramento Peak. Observations were conducted using Horizontal Grading Spectrograph (HGS), with atmospheric seeing corrected by high-order adaptive optics (AO) system. Further details of DST and AO can be found elsewhere.

The slit of the spectrograph subtended $0\farcs2$ about the middle of the sunspot, and a spatial extent of $160''$ along the North–South sunspot diameter. Four CCD cameras were used to record the spectrum in the spectral bands covering $\lambda\lambda$ 5522.039 – 5533.945 Å, $\lambda\lambda$ 5566.250 – 5588.042 Å, $\lambda\lambda$ 6293.576 – 6307.082 Å, and $\lambda\lambda$ 6551.868 – 6574.715 Å. A reflection slit-jaw image tuned through the Hα line and continuum (FOV; $160'' \times 160''$) provided context imaging, while a simultaneous G-Band image was used to provide context images as well as monitoring changing light levels.

We acquired spectral data at eight slit positions (about the central North–South cross-section of the sunspot) each separated by $0\farcs15$, in 52.5 seconds. To measure flows at the location of maximum of Evershed motions, the spectrograph slit was oriented in the direction from solar disk center toward solar limb. On the day of the observations, the sunspot was crossing central meridian, and hence, the slit was oriented in approximately the solar North–South direction.

To monitor spectral variation, 202 temporal sequences were acquired. The data were corrected for dark current and flat-fielded. From these spectra 39 well-identified spectral lines were chosen for Doppler analysis. A sample image and a corresponding spectrum in the 6300 Å region are shown in Figure 1.

3. Doppler Velocities

Each of the observed spectra were wavelength calibrated by comparing the mean flat-fielded spectrum with the Leige atlas. Doppler velocities, v, were derived from the displacement of the center-of-gravity wavelength of the spectral line, λ,

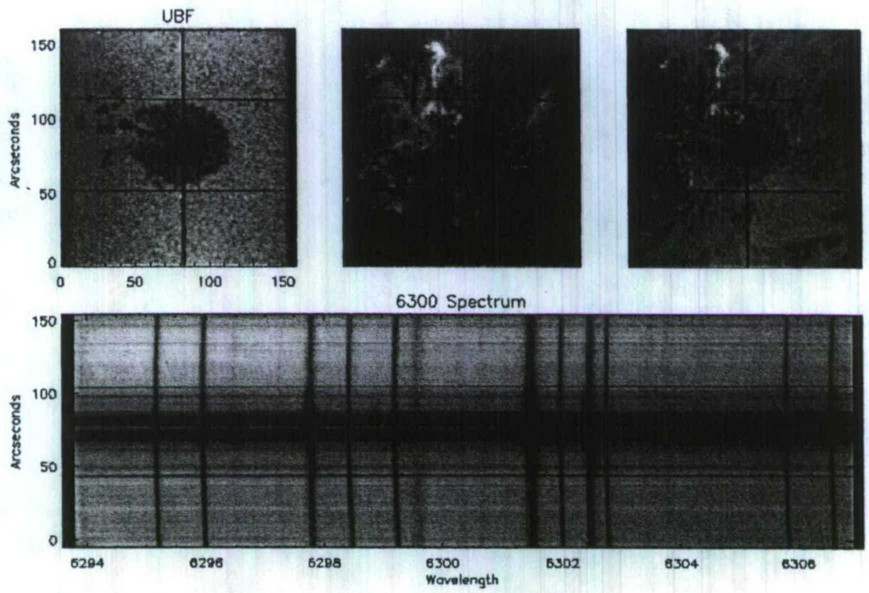

Figure 1. Reflection slit-jaw images of sunspot in continuum, Hα core and wings. The bottom panel shows the spectrum about the 6300 Å region.

relative to the mean surrounding quiet-Sun solar center-of-gravity wavelength, λ_0:

$$v = c \times (\frac{\lambda - \lambda_0}{\lambda_0}) \tag{1}$$

where c is the velocity of light.

In Figure 2, we plot the time-averaged velocities of Fe I 6301.5 Å (top panel) and Hα (bottom panel) alongside the velocity variation at a single slit position over a span of 71 minutes (middle, gray-scaled panels). Note that the average heights of formation (HOF) of Fe I 6301.5 Å and Hα for a quiet-Sun model are 400 and 2000 km, respectively (courtesy H. Uitenbroek, private communication).

There are several aspects of note in Figure 2. There is a distinct Evershed flow in the Fe I 6301 Å line, and the clear inverse Evershed flow in the Hα line, particularly outside the penumbra (chromospheric super-penumbra). These are well-known features of classic Evershed and inverse-Evershed effects. The temporal variation of these Doppler flow effects is rich in oscillatory patterns (see the middle panels of Fig. 2).

The five-minute oscillations of the photospheric (Fe I 6301 Å) quiet-Sun region are apparent, as well as the shorter period oscillations in the umbral region of the chromospheric line (Hα). Notice the variation of photospheric and chromospheric oscillations separately in the quiet Sun, super-penumbra, penumbra, umbra, and the light-bridge. The intensity and geometry of the local magnetic vector, density, and temperature appear to intricately modulate the amplitude and intensity of the oscillations.

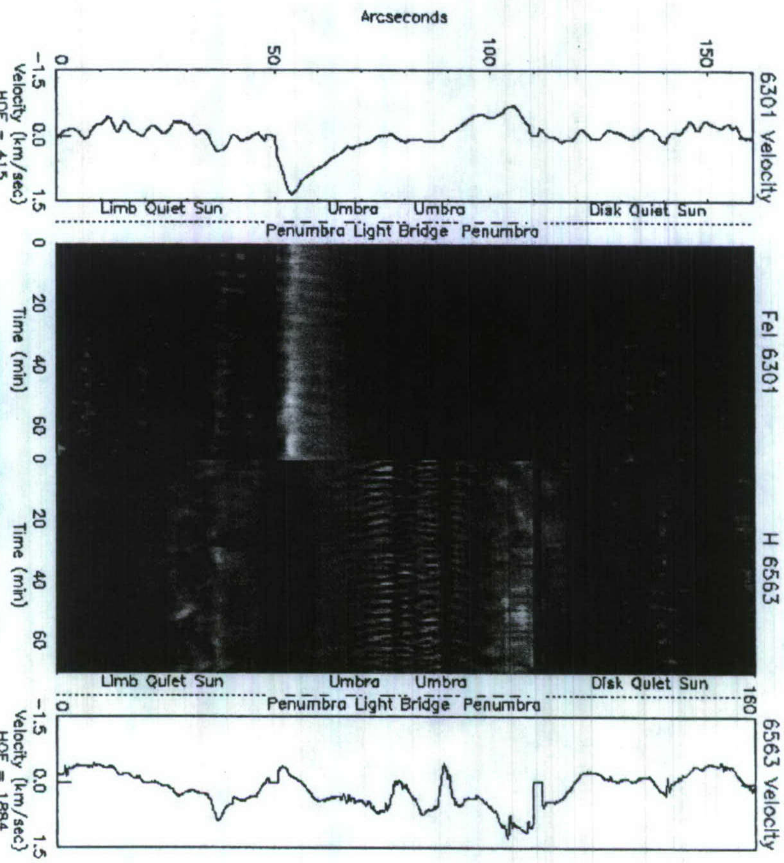

Figure 2. Mean and temporal variation of the Doppler motions across the sunspot in the photosphere (Fe I 6301.5 Å) and chromosphere (Hα 6562.8 Å). The faint vertical gray lines on either side of the spot represent the position of the quiet-Sun/penumbral boundary.

In order to understand the time variation of the Evershed flow we plot, in Figures 3 and 4, the residual Evershed flow. To derive the residual Doppler shifts, the mean Evershed velocity over the entire time is subtracted from the individual Evershed velocity measurements, at each time. The photospheric

(Fig. 3, Fe I 5576 Å, HOF= 397 km) and chromospheric (Fig. 4, Hα) residual flows are depicted. A remarkable feature seen in these images is that the residual Doppler shift appears to be made of outward-propagating Doppler packets away

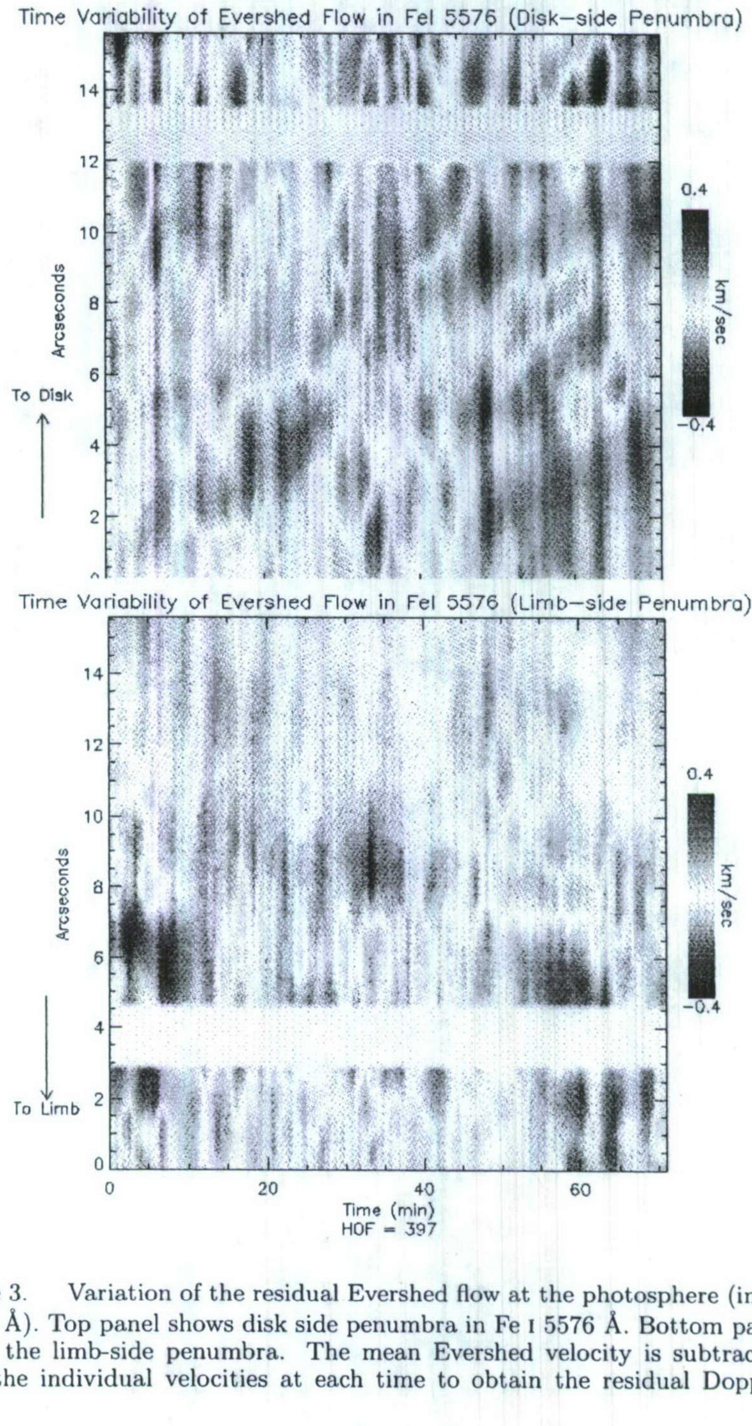

Figure 3. Variation of the residual Evershed flow at the photosphere (in Fe I 5576 Å). Top panel shows disk side penumbra in Fe I 5576 Å. Bottom panel shows the limb-side penumbra. The mean Evershed velocity is subtracted from the individual velocities at each time to obtain the residual Doppler shifts.

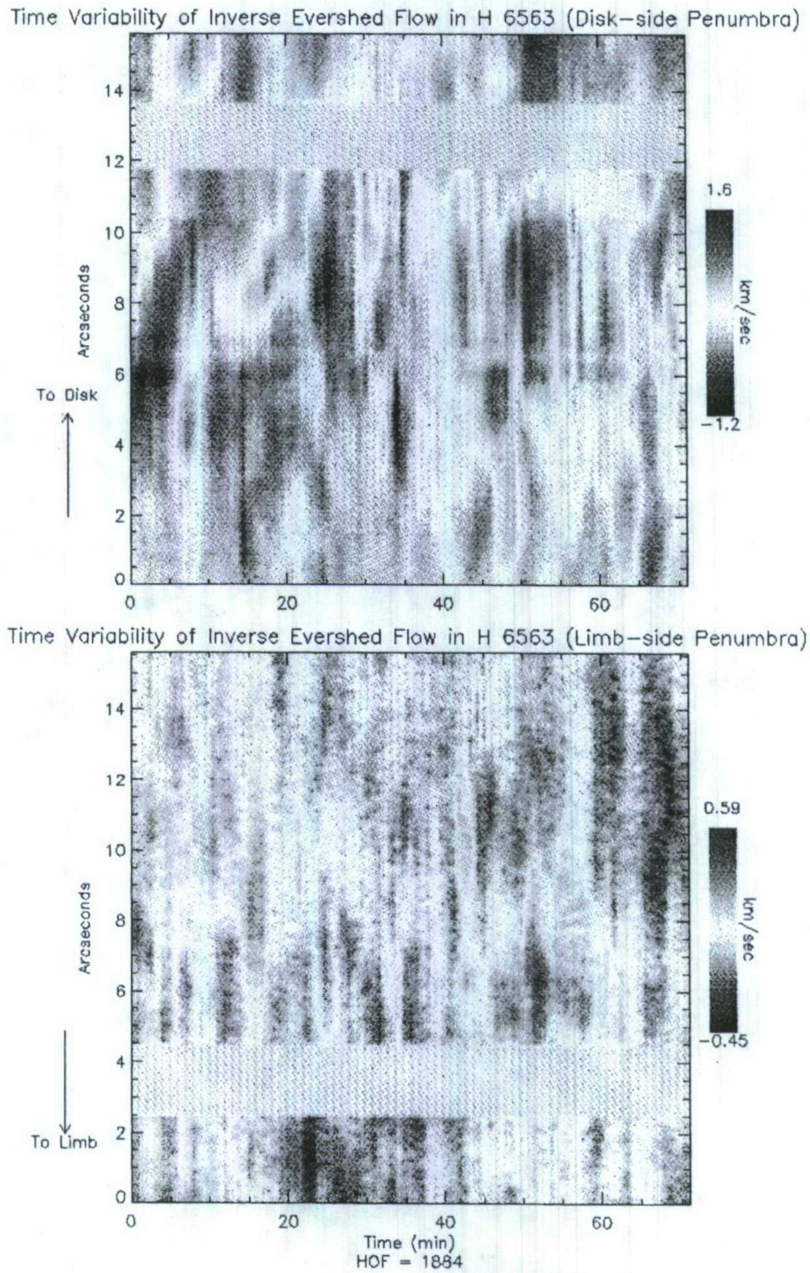

Figure 4. Variation of the residual Evershed flow at the chromosphere (in Hα). Top panel shows disk side penumbra. Bottom panel shows the limb-side penumbra. The mean Evershed velocity of the chromosphere (in Hα) is subtracted from the individual velocities at each time to obtain the residual Doppler shifts.

from the spot, both at the photosphere and at the chromosphere. That is, despite the Evershed flow being reversed in the chromosphere, the apparent propagation of Doppler packets is still outwards from the penumbra to the quiet Sun. Thus, at the chromospheric level, the apparent propagation of the Doppler packets is opposed to the direction of the flow of material, which is in agreement with other observations (Georgakilas & Christopoulou 2003). Such observations confirm the quasi-periodic behavior of the Evershed flow. It is apparent that these maxima of residual Doppler packets do not remain at a particular spatial location, but rather migrate radially outwards. At the photosphere, these packets have been interpreted by other authors (e.g., Rouppe van der Voort 2003) as "Evershed clouds" flowing outwards from the penumbra to the quiet-Sun region.

However, we also observe more than one such packet progressing radially outwards at once; another packet begins its journey before the previous has expired. Analogous images of the other spectral lines at both the limb and disk-side penumbral boundary exhibit a similar pattern.

4. Spectral Power Maps

Using the measured Doppler signals, we arrived at a power-spectral periodogram analysis of the oscillations in different parts of the sunspot. It is evident from Figure 5 that moving from the quiet Sun to the penumbral area, in the Fe I 5576 Å photospheric line we perceive an evident shift in the oscillations to higher periods. Conversely, in the chromospheric Hα line, there is a shift to lower periods in the penumbra and umbra. It is necessary to acknowledge that as we move into the sunspot, the height of formation is also being altered. We have examined the power spectrum in several other spectral lines, as well. For example, the power in Sc I 6299 (HOF= 36 km) and Fe I 6301.5 lines (not shown here) shift to higher periods, in the penumbra just like Fe I 5576. However, in the umbra the power in Sc I 6299 is highly suppressed. For example, an examination of the power spectrum of these four lines for periods up to 28.2 minutes supports the claim that the Evershed flow possesses a quasi-periodic structure. We detect an increase in power in the outer penumbra region for periods between 18–24 minutes for the photospheric lines 5576, 6299, and 6301. On the other hand, for the chromospheric Hα line , the increase in power appears between 12–18 minutes and continues out from the penumbra into the superpenumbra region. Of course, these power spectra need to be regarded with caution, since we only considered a time span of 71 minutes for this analysis.

5. Discussion

In this preliminary analysis, we have analyzed a few of the 39 spectral lines to understand the nature of the Evershed flow at different heights in the atmosphere. Our results indicate a quasi-periodicity in the Evershed flow. In the photosphere, we determined the typical time-scale to be between 18–24 minutes. These periods are slightly longer than the 8–14 minutes previously reported by Rouppe van der Voort (2003), but are comparable with the Georgakilas & Christopoulou (2003) observations (25 minutes).

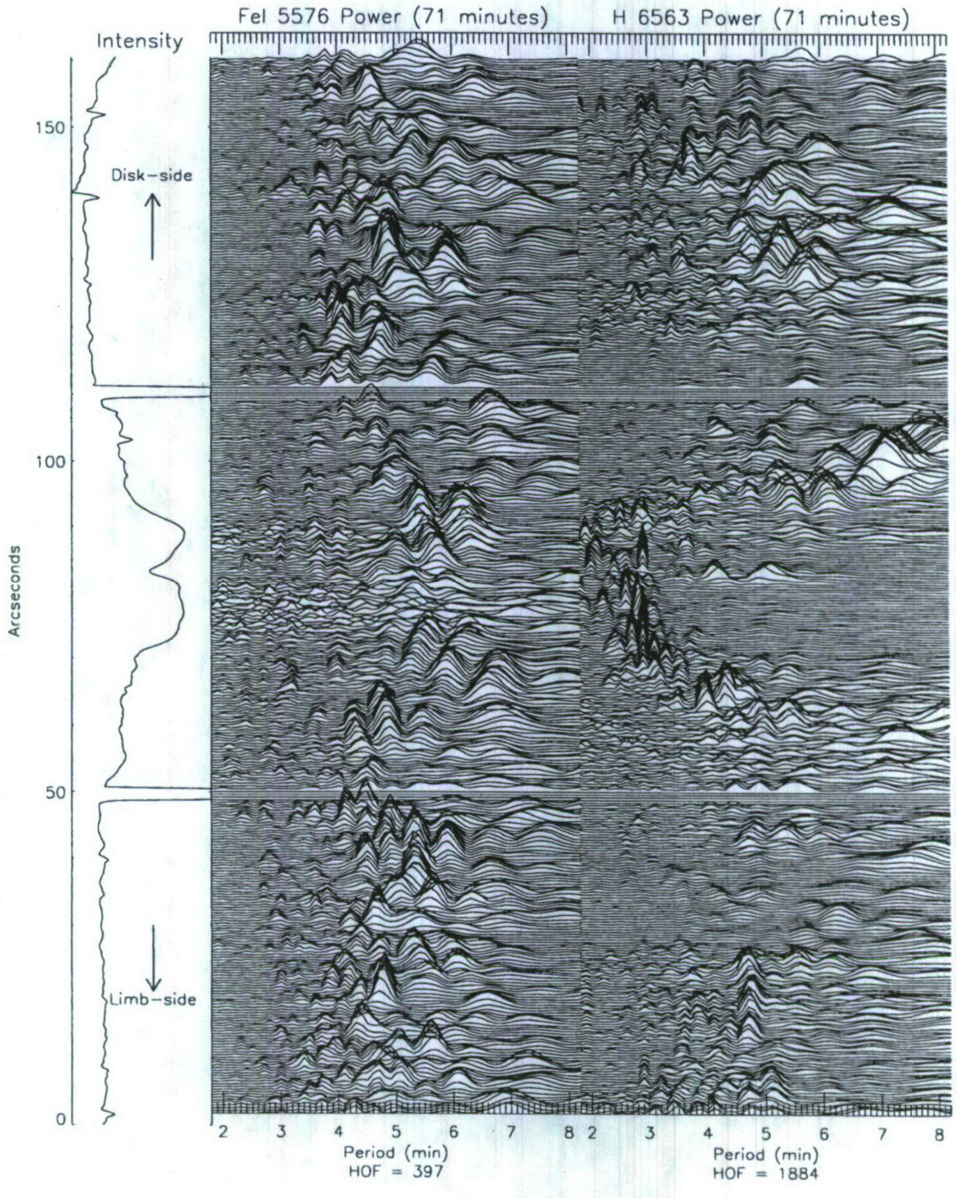

Figure 5. The spatial variation of the power in the periodicities, across a sunspot in Fe I 5576 and Hα

At the level of the chromosphere, we witnessed a characteristic time-scale between 12–18 minutes, comparable to previous results. As it was previously suggested, oscillatory pattern of (photospheric) Evershed effect may be explained in terms of pressure variation at footpoints of penumbral filaments. Rouppe van der Voort (2003) noted that 8–14 minute periodicities in Evershed flows are in agreement with the lifetime of the granular pattern outside the sunspot. He suggested that variations in pressure caused by the changing granular pattern may produce the desired effect in the Evershed flows (if the flows are siphon flows). On the other hand, he also pointed out that the Schlichenmaier (2002) moving flux-tube model exhibits "kinks" moving along the flux tube. These kinks may appear as crests of material moving outward from the sunspot penumbra. The fact that we observe longer periodicities in the photospheric layers casts doubt on the role of changing granular patterns in producing "Evershed clouds." Furthermore, our observations reveal some additional factors that further question the role of quasi-random pressure variations (due to the granular pattern) as a cause for the modulation of the Evershed effect. First, we see Evershed clouds propagating outwards both in photosphere and chromosphere. Chromospheric and photospheric clouds appear to be closely connected. Comparing the top and bottom panels in Figure 3, one can see that the "cloud" propagates faster in "limb" penumbra and slower in "disk" penumbra (c.f. the tilt of the cloud "footprint" in the time-distance plot, Fig. 3). Chromospheric clouds (Fig. 4 top and bottom panels) exhibit the very same property. Comparing Figures 3 and 4, one can notice that Evershed clouds propagate co-spatially in the photosphere and chromosphere. All of this implies that this phenomenon is caused by some global (in respect to a whole sunspot) mechanism, not by highly localized changes in granular pattern or by propagation of "kinks" in individual penumbral filaments.

One of these mechanisms may be a propagation of magneto-acoustic waves overlying quasi-steady Evershed flows. As alternative, we speculate that the Evershed clouds may be a response of the entire sunspot to oscillations propagating from below the photosphere. These oscillations may cause the sunspot to float up and down, causing a variation in the inclination of penumbral magnetic fields. This change in inclination will then be detected as a slight variation in amplitude of the Evershed flows. We will search for evidence of such global behavior of sunspot magnetic and velocity fields in the future work.

The propagation of more than one such velocity packet at a time is difficult to explain as a transient flow, supporting the belief that these packets are due to the propagation of a wave. Alternatively, if it is the outward flow of material that produces the outward propagating wave along the length of the tube at the photospheric level, it is tough to account for the outward propagation of the wave when the inverse Evershed flow is present. Hence both the siphon flow and moving flux tube model (Meyer & Schmidt 1968; Thomas 1988; Schlichenmaier et al. 1998), and the newer models for sunspots, should address the issue of outward propagating packets.

The disparity in periodicity of these flows in the photosphere and chromosphere can possibly be explained in the framework of magneto-acoustic waves in sunspots: e.g., Bogdan et al. (2003) and Khomenko & Collados (2006).

Acknowledgments. The National Solar Observatory (NSO) is operated by AURA, Inc. under a co-operative agreement with the National Science Foundation. We thank H. Uitenbroek for the calculation of the heights of formation of the spectral lines, using his n-LTE radiative transfer codes. S. Olmschenk was supported by the NSO's Research Experience for Undergraduates (REU) which was co-funded by the Department of Defence in partnership with the National Science Foundation.

References

Bogdan, T. 2000, Solar Phys., 192, 373
Bogdan, T. J., et al. 2003, ApJ, 599, 626
Crouch, A. D., & Cally, P. S. 2005, Solar Phys., 227, 1
Georgakilas, A. A., & Christopoulou, E. B. 2003, ApJ, 584, 509
Khomenko, E., & Collados, M. 2006, ApJ, 653, 739
Meyer, F., & Schmidt, H. U. 1968, Mitteilungen der Astronomischen Gesellschaft Hamburg, 25, 194
Rimmele, T. R. 1995, A&A, 445, 511
Rouppe van der Voort, L. H. M. 2003, A&A, 397, 757
Rüedi, I., & Cally, P. S. 2003, A&A, 410, 1023
Schlichenmaier, R., Jahn, K., & Schmidt, H. U. 1998, ApJ, 493, L121
Schlichenmaier, R. 2002, Astron. Nachr., 323, 303
Solanki, S. K. 2003, A&A Rev., 11, 153
Staude, J., Rendtel, J., Balthasar, H., & Zhugzhda, Y. 1999, in ESA Special Publication, Vol. 448, Magnetic Fields & Solar Processes 9th European Meeting on Solar Physics (V1 + V2), ed. A. Wilson et al., 373
Thomas, J. H. 1988, ApJ, 333, 407